Searching for New Physics with Rare B decays

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- Introduction: flavour physics within & beyond the SM
- What we learned so far: the global picture
- Looking more closely: some hints of deviations from the SM
- The shopping list of LHCb
- Conclusions
Introduction: flavour physics within & beyond the SM

natural... vs. ...artificial
Introduction: flavour physics within & beyond the SM

Particle physics is described with good accuracy by a simple and economical theory:

\[ \mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} (A_a, \psi_i) + \mathcal{L}_{\text{Higgs}} (\phi, A_a, \psi_i) \]

- **Natural**
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- **Highly symmetric**
  (gauge & flavour symmetries)

- **Ad hoc**
- Necessary to describe data (*clear indication of a non-symmetric vacuum*)
  but poorly tested in its dynamical form
- Not stable with respect to quantum corrections
- Determine the *flavour structure* of the model
Introduction: flavour physics within & beyond the SM

Particle physics is described with good accuracy by a simple and economical theory. However, this is likely to be only the low-energy limit of a more fundamentally theory:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} (A_a, \psi_i) + \mathcal{L}_{\text{Higgs}} (\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)} (\phi, A_a, \psi_i) \]

\[ \mathcal{L}_{\text{SM}} = \text{renormalizable part of } \mathcal{L}_{\text{eff}} \]

\[ = \text{all possible operators with } d \leq 4 \text{ compatible with the gauge symmetry} \]

operators of \( d \geq 5 \) containing SM fields only and compatible with the SM gauge symmetry

\[ = \text{most general parameterization of the new (heavy) degrees of freedom, as long as we perform low-energy experiments} \]
Introduction: flavour physics within & beyond the SM

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new sources of flavour-symmetry breaking that we can explore only with low-energy exps.

Two key questions of particle physics today:

- Which is the energy scale of New Physics
- Which is the symmetry structure of the new degrees of freedom

High-energy experiments [the high-energy frontier]

High-precision low-energy exp. [the high-intensity frontier]
Introduction: flavour physics within & beyond the SM

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Two key questions of particle physics today:

- Which is the **energy scale** of New Physics
- High-energy experiments
  
  [the high-energy frontier]

Strong theoretical **prejudice** that some new degrees of freedom appear around or below $1 \text{ TeV}$ to stabilise the electroweak symmetry breaking mechanism

Can we reconcile this expectation with the tight constraints of flavour physics?
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} (A_a, \psi_i) + \mathcal{L}_{\text{Higgs}} (\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)} (\phi, A_a, \psi_i) \]

3 identical replica of the basic fermion family \[ \psi_i = Q_L, u_R, d_R, L_L, e_R \]

Large global flavour symmetry: \[ U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times ... \]
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}}(A_a, \psi_i) + \mathcal{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i) \]

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Large global flavour symmetry: \[ U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots \]

Flavour-degeneracy broken the Yukawa interaction:

in the quark sector:

\[
\begin{align*}
\bar{Q}_L^i Y_D^{ik} d_R^k \phi & \rightarrow \bar{Q}_L^i M_D^{ik} d_R^k \\
\bar{Q}_L^i Y_U^{ik} u_R^k \phi_c & \rightarrow \bar{Q}_L^i M_U^{ik} u_R^k
\end{align*}
\]

\[ Y_D \]

\[ Y_U \]

\[ M_D = \text{diag}(m_d, m_s, m_b) \]

\[ M_U = V \times \text{diag}(m_u, m_c, m_t) \]

The CKM matrix

\[ \begin{array}{c} V_{\text{CKM}} \\ \downarrow \\ Y_D \end{array} \]
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} (A_a, \psi_i) + \mathcal{L}_{\text{Higgs}} (\phi, A_a, \psi_i) + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} O_{n}^{(d)} (\phi, A_a, \psi_i) \]

... while we still have a rather limited knowledge of the flavour structure of the new degrees of freedom (which hopefully will show up around the TeV scale)

We have some favourite scenarios, such as

**MFV** = assumption that the SM Yukawa couplings are the only non-trivial flavour-breaking terms also beyond the SM

D'Ambrosio et al. '02

However, at this stage these are still theoretical speculations, far from being clearly established from data

The main goal of flavour physics is trying to understand if there are additional non-trivial flavour breaking terms beside the SM Yukawas
What we learned so far: the global picture

The SM is very successful in describing quark-flavour mixing!
Good consistency of the experimental constraints appearing in the so-called CKM fits [slight tension between $\sin(2\beta)$ and $V_{ub}$, not very significant yet]

\[ V_{CKM} V_{CKM}^+ = I \]

triangular relation:

\[ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \]
What we learned so far: the global picture

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Good consistency of the experimental constraints appearing in the so-called CKM fits [slight tension between $\sin(2\beta)$ and $V_{ub}$, not very significant yet]

- Changing statistical treatment does not lead to significant differences: high-quality data are finally drawing the picture...!

- There is much more, not shown in such fits, which confirm the good success of the SM in describing flavour mixing
I. **The CKM fits** [constraints in the $\rho$-$\eta$ plane]

The most remarkable aspects of such fits is the consistency between tree-level constraints on the CKM matrix and those of $\Delta F=2$ observables:

![Diagram showing tree-level semileptonic decays and $\Delta F=2$ neutral-meson mixing](image)

Tree-level semileptonic decays vs. $\Delta F=2$ neutral-meson mixing

$$\left(\frac{y_t}{16 \pi^2 M_W^2}\right)^2 V_{tb}^* V_{td}^*$$
I. The CKM fits [constraints in the $\rho$-$\eta$ plane]

CKM unitarity triangle using only tree-level dominated amplitudes

General fit of NP in $\Delta F=2$ amplitudes

$$C e^{2i\phi} = \frac{\langle M | H^{\text{SM+NP}} | \bar{M} \rangle}{\langle M | H^{\text{SM}} | \bar{M} \rangle}$$

$\phi_{B_d}$ system

SM

neutral K

G. Isidori – Rare B decays

GGI, 22nd September 2009
I. **The CKM fits** [constraints in the $\rho$-$\eta$ plane]

These results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(\bar{B}_d-B_d) \sim \frac{(V_{tb}^*V_{td})^2}{16 \pi^2 M_w^2} + \frac{1}{\Lambda^2} c_{NP} \Lambda$$

- Contribbution of the new heavy degrees of freedom

$$\sim 1$$  tree/strong + generic flavour  $\Lambda \geq 2 \times 10^4$ TeV [K]

$$\sim 1/(16 \pi^2)$$  loop + generic flavour  $\Lambda \geq 2 \times 10^3$ TeV [K]

$$\sim (V_{ti}^*V_{tj})^2$$  tree/strong + MFV  $\Lambda \geq 5$ TeV [K & B]

$$\sim (V_{ti}^*V_{tj})^2/(16 \pi^2)$$  loop + MFV  $\Lambda \geq 0.5$ TeV [K & B]

MFV (or something very similar at least for $s \rightarrow d$ & $b \rightarrow d$), is mandatory if we want to keep $\Lambda$ in the TeV range
II. **Rare decays**

Good agreement with SM expectations is found also in rare FCNC $\Delta F=1$ decays. Most remarkable example: $B \to X_s \gamma$

**Most accurate SM th. estimate:**

$$B(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

[Misiak et al. '07]

- NNLO perturbative calculation
- Inclusive non-pert. effects using HQET
- $E_\gamma$ cut controlled by shape-function analysis
- Hard (impossible ?) to improve further in the near future...

To be compared with:

$$B(B \to X_s \gamma) = (3.57 \pm 0.24) \times 10^{-4}$$

[2009 exp. WA]
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[Misiak et al. '07]

One of the most significant constraint in many SM extensions
(with MFV as stringent as EW precision observables)

To be compared with:
$$B(B \to X_s \gamma) = (3.57 \pm 0.24) \times 10^{-4}$$
[2009 exp. WA]
III. **Vus & CKM Unitarity**

An impressive progress has been obtained also in testing charged-current interactions:

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (-1 \pm 6) \times 10^{-4} \]

Few 0.1% error!
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\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = \left(-1 \pm 6\right) \times 10^{-4} \]

Very challenging for all extensions of the SM predicting some breaking of universality between quarks & leptons (*strong e.w. symm. breaking, extra dim....*)

\[ \mathcal{L}_{\text{c.c.-eff.}} = G_{F}^{\text{CKM}} (\bar{U}_L \gamma_{\mu} D_L) (\bar{L}_L \gamma_{\mu} \nu_L) + G_{F}^{(\mu)} (\bar{\nu}_L \gamma_{\mu} l_L) (\bar{L}_L \gamma_{\mu} \nu_L) + \ldots \]

\[ G_{F}^{\text{CKM}} = G_{F}^{(\mu)} \left[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \right]^{(1/2)} \]

\[ G_{F}^{\text{CKM}} - G_{F}^{(\mu)} = \frac{c^{(i)}}{\Lambda^2} \]

bounds on \( \Lambda \) of several TeV

See e.g. Cirigliano et al. '09
Looking more closely: some “hints” of deviations from the SM
Looking more closely: some “hints” of deviations from the SM

There are a few observables where the agreement with the SM is not so good, such as

- $A_{FB}(B \rightarrow K^{*}l^{+}l^{-})$, CPV in $B_{s}$ mixing, $B \rightarrow \tau \nu$
- Non-leptonic direct CPV in $B \rightarrow K\pi$ (the so-called “$B \rightarrow K\pi$ puzzle”)
- Time-dependent CPV in $b \rightarrow s$ penguin modes

But we are still far from claiming serious discrepancies either because of limited statistics, or because of uncontrolled/underestimated theory errors, or because of both...
I. $A_{FB}(B \to K^* l^+ l^-)$

\[ A_{FB} = \int d^2 B \frac{d^2 B(B \to K^* \mu^+ \mu^-)}{d \cos \theta} \ sgn(\cos \theta) \propto \Re \{ C_{10}^* \left[ q^2 C_{9}^{\text{eff}}(q^2) + r(q^2)C_7 \right] \} \]

\( \theta = \) angle between \( \mu^+ \) & \( B \) in the dilepton rest frame
\( q^2 = \) dilepton invariant mass

- Interference of axial & vector currents \( \Rightarrow \) direct access to the relative phases of the Wilson coefficients
- Uncertainties of hadronic form factors under control in the low-\( q^2 \) region (pQCD, sum-rules)


Sensitive test of various realistic extensions of the SM (e.g. non-standard Zbs effective coupling)

Ali \( et \ al. \) '00; Buchalla \( et \ al. \) '01

[...] Altmannshofer \( et \ al. \) '09
I. \( A_{FB}(B \rightarrow K^*l^+l^-) \)

Belle has just reached an interesting sensitivity on this observable:

657 M BB,

submitted to PRL, arXiv: 0904.0770
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The agreement with SM expectations is not perfect, but claiming a significant deviation is definitely premature!

LHCb will find out if the discrepancy is serious...
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Allowed range in MFV models

Hurth, Kamenik
G.I., Mescia '08
II. CPV in $B_s$ mixing

The weak phase of $B_s$ mixing is the last missing ingredients about down-type $\Delta F=2$ transitions [$K$, $B_d$, $B_s$]: a key element to understand if there is room for new sources of flavour symmetry breaking.

**Theoretical clean extraction via** $B_s \rightarrow \psi\phi$  
[ $b+s \rightarrow ccs+s$ ]

![Diagram](image)

Experimentally quite challenging:

- Fast oscillations
- Non-trivial angular analysis
- Simultaneous fit of $\Delta \Gamma_s$ and the mixing phase
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- Fast oscillations
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- Simultaneous fit of $\Delta \Gamma_s$ and the mixing phase

A non-zero CP asym. in $B_s \rightarrow \psi\phi$ rules out both SM and MFV

Buras et al. '09
II. CPV in $B_s$ mixing

1. Reconstruct decays from stable products:
   - $B_s \rightarrow J/\Psi[\mu^+\mu^-] \Phi[K^+K^-]
   - B_d \rightarrow J/\Psi[\mu^+\mu^-] K^0[K^+\pi^-]$ (control sample)

2. Measure lifetime $ct = m_B \cdot L_{xy}/p_T
   - Proper time resolution essential to resolve oscillations

3. Measure decay angles in transversity base:
   $$\vec{w} = (\theta, \phi, \psi)$$

4. Identify $B_s$ flavor at production time:
   - Flavor Tagging (Tag decision $\xi$)

5. Perform maximum likelihood fit:
   - Likelihood in $m$, $ct$, $w$, $\xi$
Combined Tevatron result *(NEW)*

- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.

\[ \beta_s^{J/\psi} \text{ range:} \]
\[
[0.27,0.59] \cup [0.97,1.30] \text{ @68%}
\[
[0.10,1.42] \text{ @95%}
\]

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails \(\Rightarrow\) same level of SM agreement.
- Both CDF and D0 currently working on 2x samples.
- Expect improved precision by *simultaneous fit* of CDF and D0 samples.
III. $B(B \to \tau \nu)$

The helicity suppression of the SM amplitude makes $B \to \tau \nu$ an excellent probe of models with 2 Higgs doublets (such as the MSSM):

$$B(B \to l \nu) = B_{\text{SM}} \left(1 - \frac{m_B^2 \tan^2 \beta}{M_H^2 (1 + \epsilon_0 \tan \beta)}\right)^2$$

$$C_0 f_B^2 |V_{ub}|^2$$

Very clean test of the SM, provided we have reliable independent infos on $f_B$ & $V_{ub}$

**Diagram:**
- Longitudinal component of the W
- Extra tree-level contribution with simple $M_H$ & $\tan \beta$ dependence
- Up to ~30% (negative) correction in the MSSM at large $\tan \beta$
III. $B(B \to \tau \nu)$

$B(B \to \tau \nu)_{\text{exp}} = (1.73 \pm 0.34) \times 10^{-4}$  Babar + Belle '09

$(0.88 \pm 0.11) \times 10^{-4}$  UTfit '09 – global SM fit [5% error on $f_b$ ! - very dangerous]

$B_{\text{SM}} = (0.98 \pm 0.24) \times 10^{-4}$  UTfit '09 – no global fit [$f_b = 200 \pm 20$]

$(1.14 \pm 0.28) \times 10^{-4}$  [V_{ub} from UTfit '09 + $f_b = 216 \pm 21$ HPQCD '05]
Once more, it is too early to claim new physics...

...but it is certainly a stringent constraint on 2HDM & MSSM at large \( \tan \beta \), with great potential of improvement in the future.

III. \( B(B \to \tau \nu) \)

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(1.14 \pm 0.28) \times 10^{-4} \quad \text{[ } V_{ub} \text{ from UTfit '09 + } f_b = 216 \pm 21 \text{ HPQCD '05]}
\]
The “shopping list” of LHCb

High-quality flavour physics requires a good selection...
The “shopping list” of LHCb

- $B_{s,d} \rightarrow l^+ l^-$: scalar FCNCs
- $B_s \rightarrow \psi \phi [A_{CP}(t)]$: CPV phase in $(b \rightarrow s)_{\Delta F=2}$
- $B \rightarrow K^*(K) l^+ l^-$ [$A_{FB}, R^{\mu/e}, ...$]: various precise tests of $(b \rightarrow s)_{\Delta F=1}$
- $B \rightarrow D \tau \nu$: scalar charged currents
- $B \rightarrow DK$: improving $\gamma$ from clean tree-level processes
- $B_s \rightarrow \phi \gamma [A_{CP}(t)]$: right-handed currents in $b \rightarrow s \gamma$
- $B_s \rightarrow \phi \phi [A_{CP}(t)]$: CPV phase in $(b \rightarrow s)_{\Delta F=1}$
- $B \rightarrow \tau \mu$ [$&$ other LFV channels]: small chance, but worth to search for

Even being quite selective, the LHCb flavour program is quite wide, with several potentially interesting measurements.
The “shopping list” of LHCb

**** $B_{s,d} \to l^+l^-$: scalar FCNCs

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* $B \to \tau\mu$ [& other LFV channels]: small chance, but worth to search for

Rating according to the possibility of finding evidences, or constraining, realistic NP models [it reflects my theoretical prejudices: don't take it too seriously... ]
I. $B_{s,d} \rightarrow l^+ l^-$

These rare decays are both helicity suppressed and GIM suppressed (FCNC)

Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate $\tan \beta$

longitudinal comp. of the Z (one-loop indexed Z penguin) + related box amplitude
I. $B_{s,d}\rightarrow l^+l^-$

These rare decays are both helicity suppressed and GIM suppressed (FCNC)

Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate $\tan\beta$

$\begin{align*}
\text{diag}(Y_U) &= \text{diag}(m_u) / \langle H_U \rangle \\
\text{diag}(Y_D) &= \text{diag}(m_d) / \langle H_D \rangle = \tan\beta \, m_d / \langle H_U \rangle
\end{align*}$

Even in MFV, the different normalization of the Yukawa couplings induces an effective Higgs-mediated FCNC coupling:

no impact in helicity-conserving processes, but possible large effect in $B\rightarrow l^+l^-$
I. $B_{s,d} \rightarrow l^+ l^-$

Present exp. status:

$B(B_s \rightarrow \mu \mu) < 4.8 \times 10^{-8}$ (95%CL)

$B(B_d \rightarrow \mu \mu) < 7.6 \times 10^{-9}$ (95%CL)  

[CDF '09]

SM expectations:

$B(B_s \rightarrow \mu \mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \rightarrow \mu \mu)_{SM} = 1.0(1) \times 10^{-10}$

$e$ channels suppressed by $(m_e/m_\mu)^2$

$\tau$ channels enhanced by $(m_\tau/m_\mu)^2$

Within the MSSM, wit MFV:

$$A(B \rightarrow ll)_H \sim \frac{m_b m_l}{M_A^2} \frac{\mu}{\tilde{M}_q^2} \frac{A_U}{\tan^3 \beta}$$

Possible large enhancement over the SM but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

- Th. error controlled by $f_B$ (⇒lattice). Not a big issue if deviations from SM are large, but important to improve in view of future precise measurements

- The $B(B_d \rightarrow \mu \mu)/B(B_s \rightarrow \mu \mu)$ ratio is a key observable to proof or falsify MFV
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[CDF '09]

Constrained - MSSM

Buchmuller et al.


Constrained – MSSM with non-universal Higgs masses (NUHM)

SM expectations:

$B(B_s \rightarrow \mu \mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \rightarrow \mu \mu)_{SM} = 1.0(1) \times 10^{-10}$

Reaching the SM level would lead to a very significant constraint in the (C)MSSM
II. $B \to D \tau \nu$

The $\tau$ in the final state gives a good sensitivity to charged-current scalar amplitudes (large Yukawa coupling) even if the process is not helicity suppressed [typical size: ~30-40% smaller than in $B \to \tau \nu$ (assuming MFV)]

Theory uncertainty (hadronic form factors) substantially reduced (below 10%) if the rate is normalised to $B \to D e \nu$ [possible further improvement with Lattice QCD]

$$\frac{B(B \to D \tau \nu)}{B(B \to D e \nu)}_{SM} = (0.28 \pm 0.02)$$

$$\frac{m_b m_\tau \tan^2 \beta}{M_H^2 (1 + \epsilon_0 \tan \beta)}$$
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Theory uncertainty (hadronic form factors) substantially reduced (below 10%) if the rate is normalised to $B \rightarrow D e \nu$ [possible further improvement with Lattice QCD]

$B(B \rightarrow D \tau^+ \nu)_{SM} \approx 0.65\%$

$B(B \rightarrow D \tau^+ \nu) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$  
Babar '09

$B(B^+ \rightarrow D^0 \tau^+ \nu) = (1.51^{+0.41}_{-0.39}^{+0.24}_{-0.19} \pm 0.15)\%$  
Belle '09

$\frac{m_b m_\tau \tan^2 \beta}{M_H^2 (1 + \epsilon_0 \tan \beta)}$
III. $B \to D K$

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

$$\Gamma(B^+ \to f) = |A_1 + e^{i\gamma} e^{i\delta} A_2|^2$$  
$$\Gamma(B^- \to f) = |A_1 + e^{-i\gamma} e^{i\delta} A_2|^2$$

- weak phase
- strong phase
III. \textbf{B\ensuremath{\rightarrow}DK}

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

A notable exception are the \( B^\pm \rightarrow D (\overline{D}) + K^\pm \rightarrow f + K^\pm \) decays

Clean way to extract phase \( \gamma = \arg(V_{ub}) \):

- Gronau-London-Wyler/Atwood-Dunietz-Soni methods: \( B^\pm \rightarrow (K\pi, \pi\pi) + K^\pm \)
- Giri-Grossman-Soffer-Zupan method: \( B^\pm \rightarrow (K_S\pi^+\pi^-) + K^\pm \)

\textit{full Dalitz-Plot analysis}
Method shown to work at B factories: no theoretical limitations, only statistically limited

Clear room for improvements at LHCb
Back on the shopping list:

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** $B \rightarrow D \tau \nu$: scalar charged currents

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** $B_s \rightarrow \phi \gamma [A_{CP}(t)]$: right-handed currents in $b \rightarrow s \gamma$

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* $B \rightarrow \tau \mu$ [and other LFV channels]: small chance, but worth to search for
Conclusions

We learned a lot about flavour physics in the recent past...
...but a lot remains to be discovered!

We have understood that TeV-scale NP models must have a rather sophisticated flavour structure (not to be excluded by present data) but we have not clearly identified this structure yet.

Important to continue high-precision flavour physics in the LHC era.

- Progress in this field requires a collective effort in several directions: B, τ, K, μ decays, concentrating on the theoretically-clean observables [mainly leptonic/semileptonic final states]

- LHCb has the possibility to perform several unique measurements in this context